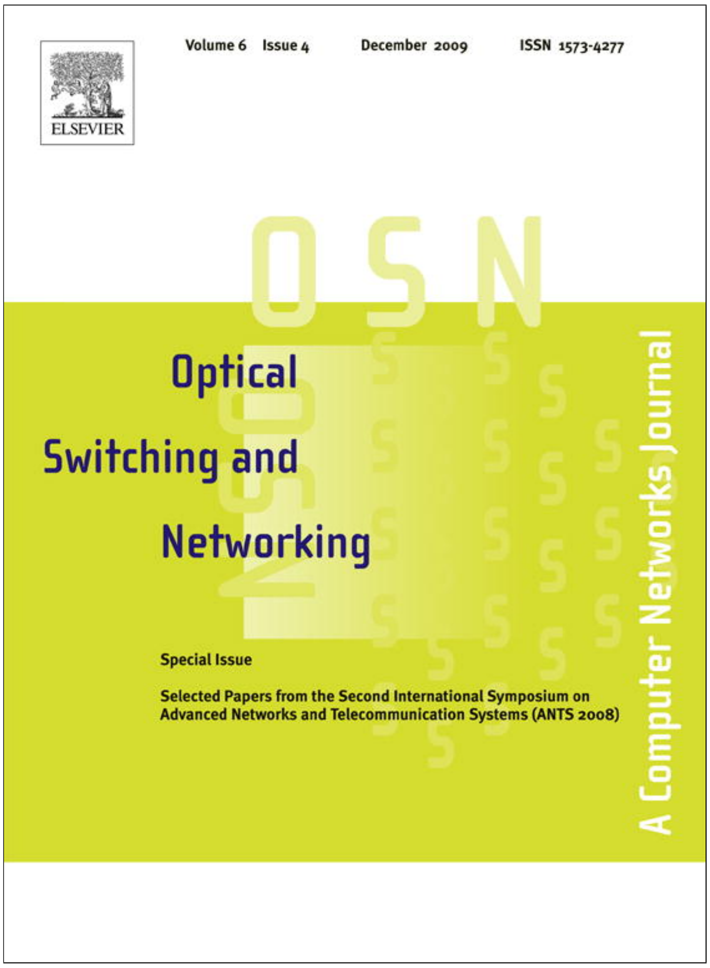
Volume 6 Issue 4 December 2009 ISSN 1573-4277
ELSEVIER
OSN
Optical Switching and Networking
A Computer Networks Journal
Special Issue
Selected Papers from the Second International Symposium on Advanced Networks and Telecommunication Systems (ANTS 2008)

Optical Switching and Networking 6 (2009) 268–275

Contents lists available at ScienceDirect

Optical Switching and Networking

journal homepage: www.elsevier.com/locate/osn

A concurrent two-layer restoration scheme for GMPLS WDM networks☆

Rabindra Ghimire [a], Seshadri Mohan [b,∗], Michael Leary [c], Terry Tidwell [c]

[a] *Applied Science Department, University of Arkansas at Little Rock, Little Rock, AR 72204, United States*

[b] *Systems Engineering Department, University of Arkansas at Little Rock, Little Rock, AR 72204, United States*

[c] *Space Photonics, Inc., 700 Research Center Blvd., Fayetteville, AR 72701, United States*

A R T I C L E I N F O

Article history:
Received 1 June 2009
Received in revised form 3 August 2009
Accepted 27 August 2009
Available online 4 September 2009

Keywords:
GMPLS
Multilayer restoration
Optical network
Survivability
Wavelength routing
WDM

A B S T R A C T

Next generation backbone networks will likely consist of IP routers as well as optical cross connects (OXCs) and will deploy an optical control plane protocol. Generalized Multi Protocol Label Switching (GMPLS) has been proposed as the candidate of choice for the control plane. Optical fibers may carry large volumes of traffic and therefore adequate mechanisms must exist to enable the network to automatically recover from failures of fiber. In mission critical networks survivability becomes very important. We investigate the problem of autonomous recovery in such networks. The literature contains work in this area that investigates the problem of multilayer recovery. Such recovery had only been sequential in the sense that the published work recovers first in the optical domain, assuming the availability of redundant resources, and then proceeds to recover packet label switched paths. We report a recovery procedure for recovering packet label switch paths (packet LSPs) and lambda label switch paths (λLSP) concurrently. We have conducted an OPNET-based simulation study that compares the performance of the concurrent scheme with the previously published sequential two-layer recovery scheme. The study shows that the concurrent two-layer recovery scheme performs as much as forty-four percent faster than the sequential two-layer recovery scheme.

1. Introduction

With the explosive growth in internet traffic, the next generation backbone networks will likely consist of IP routers as well as optical cross connects (OXCs), hereafter referred to as photonic GMPLS router [1]. The network will have the capability to perform packet switching together with wavelength path switching in order to provide quality of service (QoS). Wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM) technologies are playing a dominant role in providing high bandwidth optical transport. GMPLS has emerged as the leading control plane protocol for optical networks and utilizes the color of wavelengths as labels to establish lightpaths, referred to as lambda label switched path (λLSP) [2]. GMPLS controls both the establishment of packet label switched paths (packet LSPs) and λLSPs. In this paper, we refer to the λLSPs as the optical plane and the packet LSPs as the MPLS plane.

Photonic GMPLS routers use GMPLS as the control plane protocol. The primary components of the GMPLS protocol engine include an OSPF-TE extension module, Path Computation Elements (PCE) and a Resource Reservation Protocol module with traffic engineering (RSVP-TE). In order to provision or restore a connection, a route and a wavelength (label) must be identified for each connection. The OSPF-TE protocol distributes link state information, and determines a route for the connection; the RSVP-TE protocol reserves the necessary resources along the identified route. Consider the case in which GMPLS routers generate

☆ The research work was carried out in partnership with Space Photonics, Inc., and supported in part by the NSF Grant: EPS-0701890.

∗ Corresponding author. Tel.: +1 501 683 7475.
E-mail addresses: rxghimire@ualr.edu (R. Ghimire), sxmohan@ualr.edu (S. Mohan).

1573-4277/$ – see front matter
doi:10.1016/j.osn.2009.08.005

packet label switched paths (packet LSP) with a fixed bandwidth, routed over the optical network as λLSP. λLSPs are setup and released based on GMPLS. While λLSPs provide a coarse level of granularity, packet LSPs provide a finer level of granularity. Generally, bandwidth occupied by a packet LSP is less than the bandwidth occupied by a λLSP, since a λLSP may contain multiple packet LSPs. Consequently, to improve resource utilization, packet LSPs are merged at some node into a λLSP [3]. Reference [4] proposes a two-layer route computation in which, after the arrival of a request for packet LSP, the node first tries to find one or multiple hop routes using existing λLSP; if it is not possible to establish such a route, a new λLSP will be established. Reference [1] proposes another scheme in which after the arrival of a request for packet LSP, the node first tries to allocate a route via an existing λLSP that directly connects the source and destination with one hop. If such a route is not available the node tries to establish a new one hop path by establishing a new λLSP between the source and destination.

The emerging infrastructure could provide high bandwidth on demand, flexible and scalable support for QoS for transmission of multimedia services with small delay. Due to the large volumes of traffic a fiber carries, survivability of WDM optical networks is very important. Towards this end, we investigate the problem of autonomous recovery in such networks. Procedures for such recovery can recover either λLSPs in the optical plane or packet LSPs in the MPLS plane. The literature contains work in this area that investigates the problem of multilayer recovery, but only sequentially by first recovering λLSPs in the optical domain, assuming the availability of redundant resources, and then proceeding to recover packet LSPs in the MPLS plane. In this paper, we report a procedure for concurrently recovering in the optical and MPLS plane. The present work on concurrent recovery investigates a single link failure scenario. The OSPF-TE extension proposed here requires that the link state information propagated by the protocol must carry a total number of unoccupied wavelengths in each link and unused bandwidth in existing λLSPs. After a link failure, the nodes closest to the failure detect the failure and inform all the source nodes of the disrupted lightpath with a *Notify* message [5]. Each node then updates the network topology. The connection head end that is affected by the failure determines the availability of a new λLSP and switches over an impacted λLSP to the new λLSP in the optical plane and, concurrently, switches over impacted packet LSPs over already established λLSPs that have unoccupied bandwidth.

An OPNET-based simulation study we conducted compares the performance of the proposed concurrent scheme with the previously published sequential two-layer recovery scheme [6]. The study shows that the concurrent two-layer recovery scheme proposed here performs as much as forty-four percent faster than the sequential two-layer recovery scheme.

The remainder of the paper is organized as follows. Section 2 briefly describes multilayer routing. Section 3 provides a brief background on network survivability. Section 4 describes the proposed concurrent two-layer restoration mechanism. Section 5 presents the concurrent recovery procedure. Section 6 presents the simulation

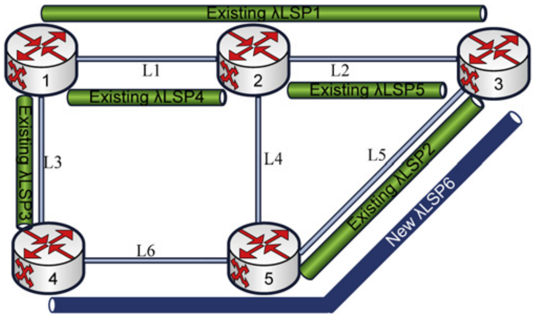

Fig. 1a. Example network.

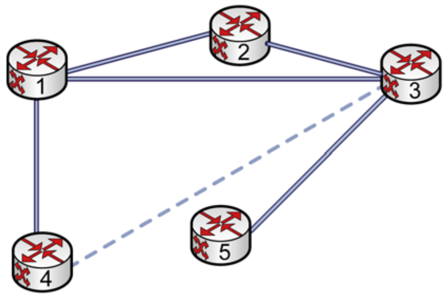

Fig. 1b. λLSP network (Virtual toplogy).

methodology and results that provide valuable insights regarding the performance of the proposed concurrent two-layer recovery scheme. Section 7 presents the conclusions from this study.

2. Multi-layer routing

Each node of GMPLS controlled optical network consists of a wavelength router, IP/MPLS router and a GMPLS route manager. The GMPLS controller in the GMPLS route manager maintains a database with information on the actual network topology and virtual topology. Control plane communications take place out of band. In such a multilayer network, a packet LSP is forwarded over a λLSP. GMPLS uses RSVP-TE to establish a packet LSP and a λLSP. If there is the arrival of a request for a packet LSP, the node first tries to find a route using an existing λLSP; if it is not possible to establish such a route, it will invoke to establish a new λLSP. Once the λLSP is established it forms the virtual topology. The OSPF-TE advertises the unoccupied bandwidth of the virtual topology which information is used for routing packet LSPs. This paper has adapted the scheme proposed in [1] in the case when there is no failure in the network, referred to as *Scheme* I. Fig. 1a shows the part of example network where $L1$, $L2$, $L3$, $L4$, $L5$ and $L6$ represent fiber links. Suppose λLSP 1, λLSP 2, λLSP 3, λLSP 4 and λLSP 5 are already established between *Node* 1–*Node* 3, *Node* 3–*Node* 5, *Node* 1–*Node* 4, *Node* 1–*Node* 2 and *Node* 2–*Node* 3, respectively. Fig. 1b represents the corresponding virtual topology of Fig. 1a. Figs. 2a and 2b show the example of RSVP signaling using *Scheme* I. As shown in Fig. 2a, upon the arrival of a request to set up a packet LSP from *Node* 4 to *Node* 3, *Node* 4 computes the path to destination *Node* 3, and initiates the RSVP-TE protocol. In order to establish a connection, destination initiated routing is used in which

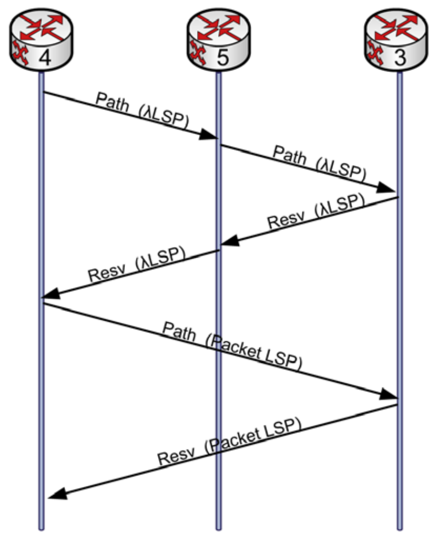

Fig. 2a. Example RSVP signaling *Scheme* I.

RSVP-TE makes use of *Path* and *Resv* messages sent in the forward (towards the destination) and backward (towards the source) direction to establish an LSP between the nodes [2]. *Node* 4 sends *Path* message via route (4-5-3). The *Path* message carry label set object that collects all the information about the availability of wavelength and wavelength converters for selecting the lightpath [5]. Upon reception of the *Path* message, the destination *Node* 3 selects one of the wavelengths and sends a *Resv* message in the backward direction along the route (3-5-4), the reverse of the path taken by the *path* message. Upon reception of the *Resv* message, assuming that a wavelength to reserve is available, *Node* 5 reserves the wavelength and forwards the *Resv* message to next hop (*Node* 4). If same wavelength is not available wavelength converters are used, which are assumed to be present at all the nodes. Once *Resv* message reaches source *Node* 4, a new λLSP is established. It is represented in Fig. 1a as a new λLSP 6. In Fig. 1b, it is represented by a dotted line. This new λLSP is then used to set up a packet LSP. Similarly, as shown in Fig. 2b, if there is the arrival of a request for a packet LSP from *Node* 1 to *Node* 4, since λLSP 3 is already established, *Node* 1 will send *Path* message of packet LSP using λLSP 3. After receiving *Path* message, *Node 4* sends *Resv* message to source *Node* 1. A new packet LSP is established if the source node receives the *Resv* message. If the *path* message encounters an error, a *path error* message is sent from that node to the source. If the *resv* message is unable to reserve resources at a node, a *path error* message is sent towards the source and a *resv error* message towards the destination. A *path tear* message is used to release the occupied resources. The pseudo code for Scheme I is shown below. The function shown in pseudo code "outgoing labels" is to calculate the label set object. The incoming resources in the pseudo code correspond to the resources from source node to a particular node and outgoing resources in the pseudo code correspond to the resources from particular node towards the destination.

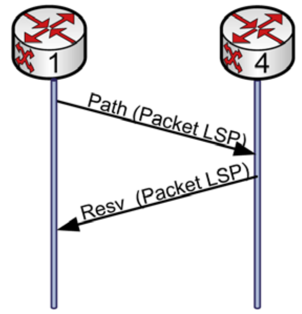

Fig. 2b. Example RSVP signaling *Scheme* I.

Function (outgoing labels)

if (this node is source)
  then outgoing labels = one of (next hop labels)
else
  {
  if (outgoing labels == incoming labels)
    then outgoing labels = incoming labels
  else if ((outgoing labels && incoming labels) is not equals to null)
    then outgoing labels = one of(outgoing labels && incoming labels)
  else
    outgoing labels = one of(next hop labels)
  }

PSEUDO CODE FOR SCHEME I

1. request for packet LSP setup
check virtual topology for route; if no route exists check physical topology
if (outgoing labels exist)
  then forward path messages toward destination
else if (no route exists or no outgoing labels)
  then path error
2. arrival of path message at a node
if (the node is not destination node and outgoing labels exist)
  then { forward path message toward destination}
else if (the node is destination and label exists)
  then occupy incoming resources and send resv message to source
else send path error toward source
3. arrival of resv message at a node
if (the node is not source and label exists)
  then {update occupied outgoing resources
    occupy incoming resources
    send resv message toward source
    }
if (the node is not source and no label exists)
  then {forward resv error toward destination
    send path error toward source
    }
if (node is source)
  then {update occupied outgoing resources;
    if (resv message is for packet LSP)
      then connection is established;
    else forward path message for packet LSP toward destination

}
4. *arrival of path error message*
if (the node is not source)
then send path error towards source
5. *arrival of resv error*
release incoming resources
if (the node is not destination)
then {forward resv error towards destination}
update released resources
6. *arrival of connection expired*
release/update resources
forward path tear towards destination
7. *arrival of path tear*
release incoming resources
if (this node is not destination)
then {forward path tear towards destination}
update released resources

3. Network survivability

Survivability of a network refers to its ability to sustain network services at the onset of network component failures. Often, to facilitate network survivability, some spare capacity, in the form of additional network components and/or transmission links, is allocated; the spare components or transmission lines are commissioned when required at the onset of failures. In any network, the layer closest to a failure will detect the occurrence of that failure, notify source end node to invoke efficient schemes to enable the network to recover from failure. The most commonly used schemes are classified under two classes—*protection* and *restoration*. *Protection* schemes establish backup paths from the installed spare capacity prior to commissioning the network, whereas *restoration* schemes establish new paths in place of the failed ones dynamically in real time. Reference [7] studies a resource efficient segment based partial protection and shows that the scheme preserves resources by utilizing only the required amount of protection segment. In *restoration*, backup paths are not established ahead of time but determined dynamically in real-time by utilizing unused resources to establish new paths in place of the failed ones. The schemes may utilize either path switching or link switching techniques.

Network survivability may be incorporated at different network layers, including the optical layer and the higher IP layer. The optical layer provides a number of advantages such as fast recovery, efficient resource utilization, and protocol transparency. Reference [8] studied the effect of nodal stub release to recover the traffic after link failure in optical domain only. Reference [9] also studied restoration in optical domain in the absence of wavelength converter and showed that during restoration contentions of resources (by RSVP-TE signaling) can block recovery attempts more than resource scarcity.

Optical layer recovery is not always able to resolve problems caused by a failure that affect higher layers. MPLS layer can deal with failures that occur at either the MPLS or optical layer but the recovery action is slow due to the finer granularity of LSPs at the MPLS layer.

This paper analyzes the two-layer recovery techniques involving both MPLS and optical layers. Multilayer recovery techniques, however, pose challenges in that they must avoid duplicating survivability functionality in multiple layers that may cause routing instabilities and reduce resource utilization [6]. References [6,10,11] have studied different multilayer survivability techniques. Reference [6] proposes sequential multilayer recovery schemes for IP over WDM that utilizes a hold-off timer and a recovery token and shows that the scheme using recovery token outperforms that using the hold-off timer. Reference [12] provides a quantitative case study of recovery in multilayer networks and shows that well considered coordination is most important in order to obtain high performance recovery. Reference [13] presents a model that uses a QoS rerouting model and a hybrid resilience framework to reduce the recovery time and increase the level of restoration in multilayer networks. It shows that the hybrid resilience framework where restoration is deployed in the MPLS domain while protection switching is implemented in the optical domain leads to the best recovery performance.

4. A concurrent two-layer restoration scheme

In contrast to the sequential recovery scheme in [6], we propose a novel concurrent two-layer restoration scheme that, after detecting a failure, initiates recovery concurrently both in the optical layer and the MPLS layer. We show using OPNET-based simulations that our scheme speeds up the recovery process by 44% when compared to the sequential recovery scheme. Our study has also led us to propose new extensions to the OSPF-TE protocol that should have far reaching implications beyond just concurrent recovery to new protocols for dynamic bandwidth assignment in DWDM networks.

In any typical optical network, OSPF-TE floods the summarized information of network topology. It advertises the network link as alive as long as free capacity is available. Reference [14] proposes extending OSPF-TE for GMPLS by advertising actual unoccupied bandwidth on the TE link between adjacent nodes to manage resources. Total unoccupied bandwidth refers to the total bandwidth available in a fiber equal to the sum of unoccupied bandwidth in all wavelengths, as some wavelengths may be partially used. The total unoccupied bandwidth provides a clear idea about the number of packet LSPs that can be accommodated in the fiber but it is difficult to determine how many new λLSPs can be established from source to destination. In order to facilitate concurrent two-layer recovery, we propose an extension to the OSPF-TE routing protocol in support of carrying link state information for GMPLS. While sharing the link state information, in addition to total unoccupied bandwidth in existing λLSP, if the information about the total number of unoccupied wavelength in each link is also shared, this information can be used for concurrent recovery as we proceed to show.

Fig. 1a illustrates a segment of the network with six links, with each link carrying multiple wavelengths. For example, at some time instant t_0, one or more of the wavelengths may be occupied. Suppose that the number of unoccupied wavelengths in each link is as shown in

Table 1
Number of unoccupied wavelength in example network.

From	To	Link	Distance	Unused lambda LSP
1	2	L1	1	2
1	4	L3	1	1
2	1	L1	1	2
2	3	L2	1	3
2	5	L4	1	0
3	2	L2	1	3
3	5	L5	1	2
4	1	L3	1	1
4	5	L6	1	1
5	2	L4	1	0
5	3	L5	1	2
5	4	L6	1	1

Table 2
Number of unoccupied wavelength after link failure.

From	To	Link	Distance	Unused lambda LSP
1	2	L1	infinite	0
1	4	L3	1	1
2	1	L1	infinite	0
2	3	L2	1	3
2	5	L4	1	0
3	2	L2	1	3
3	5	L5	1	2
4	1	L3	1	1
4	5	L6	1	1
5	2	L4	1	0
5	3	L5	1	2
5	4	L6	1	1

Table 1. Upon failure of link *L*1 at time instant t_0^+, the nodes close to the failure detect the failure; inform all the source nodes of the disrupted lightpath with a *Notify* message. Assuming no arrival and departure during this interval, the routing table will be updated as shown in Table 2; a similar table exists for virtual topology that represents unoccupied bandwidth in existing λLSPs. The failed link may carry traffic from various sources. As soon as the source node receives *Notify* message it starts a *timer* and applies a scheme we refer to as *Scheme* II for routing the traffic. In *Scheme* II, the affected source node checks the updated database for the availability of new λLSPs from source to destination as well as any unoccupied bandwidth in the existing λLSPs that connects the source to destination. If sufficient numbers of new λLSPs can be established to recover the affected traffic, the source node invokes λLSP setup request and λLSPs are setup using RSVP-TE. If new λLSPs are not available, then packet LSPs are switched using unoccupied bandwidth in existing λLSPs appearing in the virtual topology. If only a few new λLSPs can be established, but are not sufficient to recover all the affected traffic, the source node will switch some λLSPs via new λLSPs, and the remaining via packet LSPs using unoccupied bandwidth of existing λLSPs concurrently.

Fig. 3 shows RSVP-TE signaling to recover traffic, assuming link *L*1 in Fig. 1a has failed. Suppose only two lightpaths λLSP 1 and λLSP 4 are affected by the failure. In this case, since the information about the unoccupied free wavelengths and unreserved bandwidth of existing λLSPs (virtual topology) are shared in the link state information, the decision whether to recover in optical plane or in MPLS plane can be made concurrently. In this case, upon receipt of *Notify* message, *Node* 1 triggers timer and switches the routing scheme to *Scheme* II. *Node* 1 uses *Scheme* II till the expiry of the timer and again switches back to *Scheme* I explained in multilayer routing. From the link state information shown in Table 2, *Node* 1 knows both λLSP 1 and λLSP 4 cannot be recovered in the optical plane. Only one new λLSP can be established either to reach *Node* 2 or *Node* 3. If a new λLSP is established to recover λLSP 4 via route (1-4-5-3-2, assuming the availability of wavelength conversion at each node), λLSP 1 cannot be recovered in the optical plane, so the traffic in λLSP 1 needs to be switched in the MPLS plane using multiple hops (i.e. using λLSP 3 and λLSP 6) assuming that sufficient unoccupied bandwidth is available. As shown in Fig. 3, *Node* 1 sends a *Path* message to setup a new λLSP via route (1-4-5-3-2) to recover λLSP 4 and *path* messages to create packet LSPs via route (1-4-3) to switch affected traffic of λLSP 1. After receiving the *Path* message, the destination node reserves the path traversed by the *Path* message by sending a *Resv* message in the reverse direction taken by the *Path* message. When the source node receives the *Resv* message, it switches one of the affected packet LSPs whereas after receiving the *Resv* message for λLSP, all the traffic carried by λLSP 4 will be switched over to the new λLSP. There might be many concurrent *Path* messages for λLSPs and packet LSPs, depending on the affected traffic.

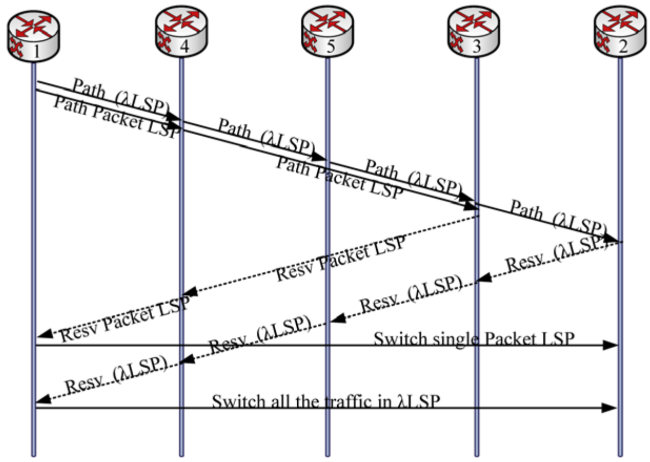

Fig. 3. Example RSVP signaling for concurrent recovery *Scheme* II.

Function (initialize recovery)

1. affected lightpaths = number of affected lightpaths
2. matrix χ = physical topology
3. matrix ψ = virtual topology
4. **for** (i = 1: affected lightpaths)
   { compute route(i) using matrix χ
   if (route exists)
   then { update matrix χ
      save route lambda(i)
      }
   else
      {affected packet LSP = number of packet LSP in
       path (i)

```
        for (k = 1: affected packet LSP)
          {compute route(k) using matrix ψ
          if(route exists)
            then { update matrix ψ
                   save route packet(i,k)
                 }
          else no route
          }
        }
      }
```
5. for all available routes, forward path messages towards destination

So, with the availability of wavelength conversion and the availability of number of unoccupied wavelengths together with unoccupied bandwidth in existing λLSPs, each node can decide which of the failed lightpaths can be recovered in the optical domain and which ones in the MPLS domain and take actions to recover them concurrently. Note that in the absence of wavelength converters, connections must be established using the same wavelength, as originated by the destination, on each link in its route. In such a case, contention may occur where two or more connections try to reserve the same wavelength in a particular link along the route thereby increasing blocking. In this case, since wavelength converters are present, blocking occurs only if there is a scarcity of resources. Consequently, concurrent recovery will be considerably faster than sequential recovery as we demonstrate in this paper. The pseudo code for *Scheme* II is also included in the paper. The function "initialize recovery" checks for the availability of route in optical domain, if a route is not available, it looks for one in the MPLS domain.

PSEUDO CODE FOR SCHEME II

1. arrival of notify message
if (the node is affected source)
  then {
    trigger notify timer to true
    schedule the expiry of notify timer
    compute lightpaths affected by failure
    forward path tear for affected lightpaths
    initialize recovery ()
    }
2. arrival of resv message and notify timer is true
if (the node is source)
  then {
    update occupied outgoing resources
    connection recovered
    }
3. arrival of path error and notify timer is true
if (the node is source)
  then {
    compute lightpaths affected by failure
    initialize recovery ()
    }
4. arrival of expiry notify timer
trigger notify timer to false

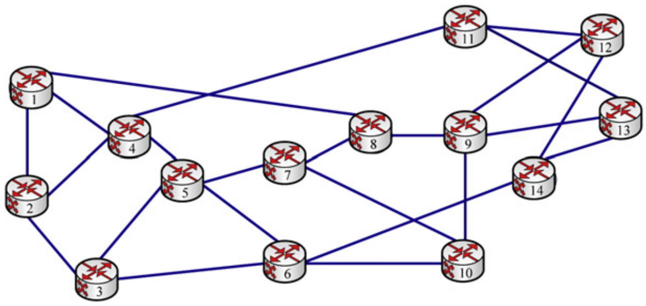

Fig. 4. Modified NSFNET model.

5. Recovery procedure

In order to perform concurrent recovery, the nodes close to the failure detect the failure and inform all the source nodes of the disrupted lightpath with a *Notify* message. As soon as a source node receives a *Notify* message it triggers a *timer* and uses *Scheme* II for routing the traffic. Consider the modified NSFNET network shown in Fig. 4. Suppose that the link between *Node* 8 and *Node* 9 fails; *Node* 8 and *Node* 9 will detect failure. If the traffic that originated from *Node* 8 and *Node* 9 (assuming *Node* 8 and *Node* 9 are also source node) are affected by the failure and a new λLSP cannot be established, recovery will begin by switching packet LSPs using unoccupied bandwidth in virtual topology. Similarly, other ingress nodes affected by failure also check for the availability of new λLSPs and unreserved bandwidth in existing λLSPs from source to destination. If two or more λLSPs originated from a single node were affected by the failure, the node will first determine those that are recoverable in the optical domain and those recoverable in the MPLS domain. If i number of λLSPs (lightpaths) out of j λLSPs (lightpaths) ($j > i$) are recoverable in the optical domain, it will invoke i new λLSPs and the traffic of ($j - i$)λLSPs will be recovered by using one or more hops of the virtual topology (i.e., using unoccupied bandwidth of existing λLSPs) concurrently. The routing protocol may take a finite time to update the link state information (i.e., LSP occupied or released) to its neighbor and effect the route calculation. Though we have not done an additional simulation to reflect the effect of time parameters, qualitatively, we do observe that if link state update time were to increase, blocking probability will increase.

Here, we assume that changes in link state information are advertised to all other nodes immediately. During simulation, the database is updated after 0.5 ms at neighboring nodes connecting the failed link and those that are N hops away from failed link are updated after N*0.5 ms (same is the case for virtual topology). If blocking occurs during the path reservation process, the upstream node sends back a path error message. The ingress node will check the updated data base and repeat the process till the expiry of timer triggered by the affected node. Since ingress nodes will compute which of the lightpaths are recoverable in the optical layer and which ones in MPLS layer, there is no possibility of duplicate attempts to recover the same lightpath at both layers.

5.1. Simulation details

Upon receipt of the failure notification by the ingress node, the following steps are undertaken by simulation.

Step 1: Ingress node calculates the number of λLSPs (lightpaths) that are affected.

Step 2: Matrix χ is constructed based on the physical topology and the availability of unoccupied wavelengths. Each element of matrix indicates the number of unoccupied wavelengths in the links between adjacent node pairs.

Step 3: Matrix ψ is constructed depending on the current virtual topology, with each element in the matrix representing total unreserved bandwidth of existing λLSPs (lightpaths) between adjacent node pairs.

Step 4: Dijkstra's shortest path algorithm is used to find the new λLSP with the least hops from source to destination depending on matrix χ.

Step 5: If the number of available new λLSPs is greater than or equal to the number of affected λLSPs, go to Step 7, else go to Step 6.

Step 6: Dijkstra's shortest path algorithm is used to find the shortest path depending on matrix ψ. Weight is assigned to avoid congestion while selecting the path.

Step 7: Decide how many of the affected λLSPs can be recovered in optical layer and how many in MPLS layer.

Step 8: If no path exists reject the LSP request and terminate the process otherwise go to Step 9.

Step 9: LSP setup request is invoked and paths are reserved.

Step 10: If an error message is received during reservation process go to Step 1. This process is repeated a maximum number of times prescribed by a counter or till the expiry of timer set by the affected node.

6. Performance

We evaluate the performance of the proposed scheme by using OPNET. The simulation is repeated 25 times with different random seeds. The results are averaged and confidence intervals at 95% confidence level are calculated. The performance of the proposed concurrent system is compared with that of the sequential two-layer recovery using recovery token proposed in [6]. The modified NSFNET model consisting of 14 nodes and 23 links shown in Fig. 4 has been simulated. We assume that each adjacent node pair is connected using a single bidirectional fiber carrying $C = 16$ wavelengths. We further assume that wavelength converters are deployed at all network nodes. Traffic demands are assumed to be uniformly generated throughout the network, and there is equal probability of choosing any node as source or destination node.

The simulation parameters are shown in Table 3. At all the nodes, a request for packet LSP setup follows the Poisson distribution with rate λ and the destination for the request was uniformly selected. The holding time of connections was exponentially distributed. For each simulation, the mean holding time of each packet LSP is assumed to be 100, and the arrival rate λ is varied to achieve the desired load (ζ). The required packet LSP bandwidth normalized by wavelength bandwidth is set to 0.0625. The ratio of unused wavelength to total wavelength in a fiber link equals 0.25. The average number of packet LSPs carried by a single wavelength equals 11. Each of the links between the nodes has equal probability of failure and single link failure is assumed for the simulation.

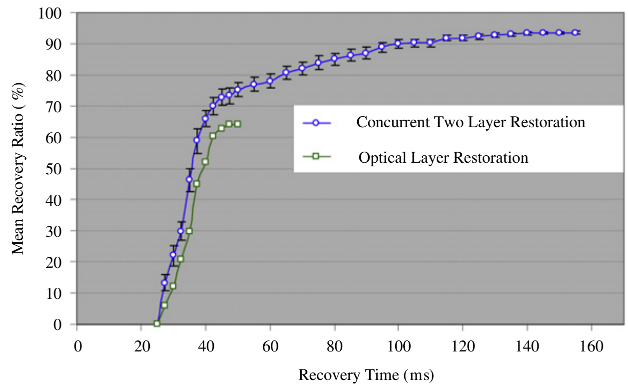

Fig. 5. Comparison of concurrent two-layer restoration with optical layer restoration.

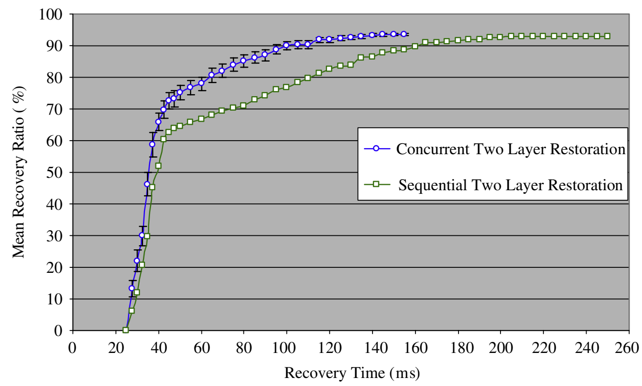

Fig. 6. Comparison of concurrent two-layer restoration with seequential two-layer restoration.

The physical topology reconfiguration time and virtual topology reconfiguration time are assumed to be equal to 25 ms. The packet processing time is 1 ms. The propagation delay on each link is 0.5 ms. The wavelength reservation time is 1 ms. A λLSP is invoked if there is arrival of a single packet LSP and is torn down if it does not accommodate any packet LSP. Figs. 5 and 6 illustrate the performance of the proposed algorithm and compare it with that of single layer restoration in the optical domain and sequential two layer restoration scheme of [6].

Fig. 5 shows that at 42 ms, with only optical layer restoration, about 60% of the affected traffic can be recovered, whereas with concurrent two layer restoration about 70% of the affected traffic can be recovered. This implies that the excess traffic of 10% was recovered in the MPLS domain. The optical layer recovery can recover a maximum of about 65% of affected traffic where as concurrent two layer recovery scheme can recover about 93% of the affected traffic.

Fig. 6 compares the proposed two-layer concurrent recovery algorithm with the sequential two-layer restoration scheme with recovery token. The figure shows that at 105 ms, the concurrent two-layer recovery scheme

Table 3
Simulation parameters.

Arrival of packet LSP	Possion
Holding time of packet LSP	Exponential
Ratio of packet LSP bandwidth to wavelength bandwidth	0.0625
Ratio of average unused wavelength to total wavelength in a link	0.25
Average number of packet LSP carried by single wavelength	11
Physical topology reconfiguration time	25 ms
Virtual topology reconfiguration time	25 ms
Packet processing time	1 ms
Propagation delay on each link	0.5 ms
Wavelength reservation time	1 ms

recovers 90% of the traffic whereas the sequential two layer mechanism recovers only 78% of the affected traffic. Both schemes can recover about 93% of the traffic, with the concurrent scheme requiring only 137 ms in contrast to the sequential requiring more than 245 ms. Consequently, our concurrent scheme achieves a speedup of about 44% over the sequential scheme. In essence, given that a certain level of recovery must be achieved, the concurrent scheme will recover faster compared to the sequential scheme. Alternatively, given a fixed amount of time for recovery, the concurrent scheme will achieve a greater level of recovery compared to the sequential scheme.

7. Conclusions

This paper presents a novel scheme for concurrent two-layer restoration in optical networks. An extension to the existing OSPF-TE has been proposed and employed in this scheme. The performance of the scheme is evaluated and compared with the previously published sequential recovery scenario. OPNET-based simulations reveal that, to recover the same percentage of traffic after the onset of a failure, the concurrent scheme can achieve a speedup of as much as 44% over the sequential recovery scheme. The OSPF-TE extension we have proposed will find applicability beyond the concurrent scheme to dynamic bandwidth allocation schemes in GMPLS-based DWDM networks. Future extensions may involve the development of a hybrid scheme that combines the concurrent scheme with path protection procedures and evaluate the performance of the concurrent and hybrid schemes using an optical networking testbed.

Acknowledgements

A short summarized version of this paper was presented at the Second Symposium on Advanced Networks and Telecom Systems (ANTS) 2008 in Mumbai, India, in December 2008.

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